Quantitative Assessment of the Criticality Level of Organizational System Elements

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Abstract

This paper discusses various aspects of determining quantitative indicators of the criticality level for elements of a complex organizational system. The concept of the criticality level of organizational system elements is introduced and formalized. The problem statement of determining the criticality level of elements is defined. Approaches to determining the limit values for critical elements of the organizational system are suggested. Features of relationships between functions performed by elements of the organizational system are described. The main aspects of the system activity and the measurement scale for determining the criticality level of elements are reviewed. Both resources used by the elements of the system to ensure its vital activity and flows that characterize the activity of the system are indicated. Approaches to the assessment of aspects of the system and features of using the quantitative scales while calculating the relative criticality level of system elements are described. Formulae are also given for values normalization of elements functioning parameters as well as approaches to the objective aggregation of various values of the parameters into a single integral indicator for each element of the system. Additional information has been studied that can be used for a comprehensive and objective study of the criticality level of the organizational system elements and an adequate determination of a integral indicator of the criticality level for each element.

Keywords

Critically important elements, criteria, quantitative indicators, criticality level, decision-making, normalization of parameter values, data aggregation

1. Introduction

Functional stability (FS) of a system is an important characteristic of operating of a complex organizational system (COS), along with reliability, survivability, and fault tolerance. This property indicates the level of sustainable performance of COS purpose and the system security from external threats. FS testifies to the ability of COS to maintain a given level of performance quality of the functions, they are the purpose of developing the system, and the system is designed to perform them [1, 3]. These functions must be performed under any conditions, despite the damage, various extraneous influences, management errors, failure of some COS subsystems, equipment failures, and various environmental disturbances during the system operation [4, 5]. Reasonable and adequate approaches to assessing the quality of system functioning allow for formalizing the task of maintaining FS and responding to external influences in a timely manner [6].

Critical elements (CE) are extremely important factors influencing the functioning of COS in general [7, 8]. The definition of such elements and the features of their influence on the system will be given below. The main characteristics of CE with a significant impact on the activities of COS will also be investigated, and approaches to the quantitative determination of the performance indicators of the elements and subsystems of the organizational system will be proposed. Thus, the patterns of

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providing FS of COS will be studied more deeply. This, of course, will entail the need to generate new approaches to the provision of FS and affect the development of appropriate strategies for managing COS.

The definitions of criticality are the main features for defining CE of COS:

- by functionality, not by job titles, level in the hierarchy, or competencies of employees;
- with a mandatory adjustment for the authority of the employee in the performance of functions;
- for the impact on the activities of COS in general (image, brand, goodwill, etc.);
- by direct or indirect influence on the external manifestations of COS (PR, sales level, legend sustainability, etc.);
- according to the criticality of the main flows in COS (goods, finance, information, etc.);
- by influence on internal relationships (mission, vision, corporate culture).

The purpose of this work is to analyze and quantify CE based on direct and indirect data:

- set of persons to whom CE is subordinate in this or that kind;
- set of persons subordinate to CE;
- flows passing through CE;
- functional duties and responsibilities of CE;
- CE with the authority and the availability of means for exercising these powers;
- dependence of the functions performed by other elements of COS on the quality of the functioning of CE;
- time and expenses of COS for the training and adaptation of new employees for this position;
- difficulty in replacing CE if necessary.

2. Problem statement

Let some set of indices of functions that should be provided by COS be given. Let some set of indices of functions that should be provided by COS be given. We will assume that there will be n such functions. Let us denote the set of all functions performed as $A = \{a_1,...a_n\}$, $J = \{1,..., n\}$. A complex system may perform hundreds or thousands of functions that are not duplicated, that is, $n = \sum_{i \in J} n_i$ – each function in the system is unique: $A^{i_1} \cap A^{i_2} = \varnothing, i_1, i_2 \in J$, where $\varnothing$ is an empty set [6].

There are CE among the elements of COS. In this work, the criticality levels of elements will be proposed and studied in order to ensure the qualitative performance of their functions, if necessary, their motivation, etc.

The relationship between functions and the sequence of their execution is given by a binary relation B, which is a subset of the Cartesian product $A \times A$. The binary relation B is built in accordance with the consistency of some organizational system and reflects an approach to solving issues faced by the system elements [9, 10]. Moreover, the performance of each function of the system is provided by some element of the system $e^i, i \in I = \{1,..., k\}$ and can be performed by some other element $e^j, i \neq j,\ i, j \in I,$ – in the general case with different degrees of quality – that is, redundancy is embedded in the system [3, 7].

3. Some aspects of COS functioning and critical elements of COS

It is necessary to monitor characteristics grouped by some features to analyze data and decide on the criticality level of elements [11-13]. It is advisable to consider the following aspects of the elements of a complex semi-structured system, which are the nodes of a graph that models a specific system in a certain subject area [14, 15]:

α_1 – impact on system resources;

α_2 – flows that the element controls;

α_3 – impact on decision-making in the system;

α_4 – a set of managerial influences on the system elements;

α_5 – frequency or participation in responding to multiple requests processed by the system;

α_6 – access control to significant features of the system;

α_7 – a set of graph edges providing information to the vertices;

α_8 – a set of graph edges modeling the reconciliation procedures for decision-making in the system.

Modern organizational systems are characterized by incompleteness, inaccuracy, and irrelevance of information [16-18]. This is due to various reasons:

- irregular monitoring of the organization's activities;
- confidentiality of information;
- unavailability of data;
- insufficient qualification of the personnel providing the information system;
- different reference coordinates in data arrays;
- variability of operating conditions of organizational systems;
- dynamic changes in the environment that the organizational system interacts with.

If the status and health of system elements significantly impact the system or its major parts, such elements are considered critical parts (element, node, layer, subsystem) of the system. Relations between elements can be represented as a multi-connected graph. If some vertices of the graph in case of failure of related elements affect the decrease in FS or the loss of connectivity of a significant number of graph nodes, such vertices are considered critical nodes. Therefore, all other elements of the system are not critical and will be named linear.

Critical elements play an important role at all stages of providing FS of COS and in all aspects of decision-making on the management of FS. To determine the level of influence of the CE on the functioning of the system, it is necessary to introduce the concept of criticality level (CL). CL is a numerical indicator that reflects the integral influence of the CE on the quality of the functioning of the system as a whole.

The main goals of determining the quantitative CL of system elements are:

- increased danger for the system due to failures of CE functioning;
- the significant impact of CE on the quality of functioning of the organizational system;
- the indispensability of CE or issues with the quality performance of the functions performed by CE.

The main features and key characteristics of CE in COS are:

- have the appropriate level of access and authority for exceptional actions;
- have resources by orders of magnitude greater than ordinary elements and the authority to manage them;
- their activity costs significantly higher than other elements;
- have a significant impact both on the elements of the lower level of management and on the elements of the upper levels of the COS hierarchy;
- have a significant indirect impact on the system, subsystems, and other elements that could be higher than direct impact;
- manage elements with high CL;
- in case of failure, their subordinate elements bear significant losses, as well as the system itself;
- they have a significant number of various connections with other elements and, as a rule, act a nodal role.

Expert decision-making technologies are used to quantitatively determine the criticality level of elements. Quantitative characteristics for graph vertices could be determined by means of incident matrix also known as the Kirchhoff (Laplace) matrix. Some integral values that reflect the number, importance and complexity of documents passing through administrative and other flows can be considered as the weight of the edge.

4. Resources and flows in COS

Let us consider in more detail parameters [19, 20], which can be useful in some aspects [10, 21]. An in-depth analysis of all available system resource should be conducted to determine the influence by a system element on its resources [6, 8]:

α_{11} – human (labor) resources – number and quality of personnel, staffing, the perfection of the organizational structure, the quality of corporate culture;

α_{12} – financial resources – currency, securities, percentage of liquid resources in the investment portfolio;

α_{13} – material resources – equipment with fixed assets, the level of physical and economic security;

α_{14} – intangible resources – goodwill, modern technologies, brand;

α_{15} – information resources – availability of external information, orderliness, security of internal information, computing power, and reliability of communication tools.

The more critical element will be the one that has a greater impact on the specified resources regardless of the level of use (operational, tactical, strategic, etc.). In context of the first aspect CL of the element is calculated by the formula $f_1\left(\alpha_{11}^i,...,\alpha_{15}^i\right)$, where i, $i \in I$ – are the indices of the system elements, parameters could be given tabular or analytically.

The elements of the system are controlled by the flows that have a significant impact on them, that is why the flows should be analyzed too [22, 23]:

α_{21} – financial flows;

α_{22} – material flows;

α_{23} – information flows;

α_{24} – service flows;

α_{25} – managerial influences.

The characteristics of a function may include various types of flows that need to be operated to perform this function.

5. The structure of COS and the complexity of replacing CE as a criterion for the CL

The following components should be considered when simulating COS:

- place of CE in the COS hierarchy (for example, the management level of the element, direct subordination to the top-level element, subordination to sets of elements from lower levels, functional subordination, basic functions, the quality level of functions, adjacent functions, the quality level of adjacent functions);
- establishment of hierarchical connections between elements of the system and determination of effect levels for one item on another or no effect;
- effect level on the subdivision that contains the element;
- effect level of the subdivision leading element on other subdivisions;
- effect level of the subdivision leading element on the whole system;

- interactions between subdivisions are affected significantly by functional subordination of elements;
- effect level according to the staffing table with double and triple subordination;
- interaction between elements in accordance with functional interactions between subdivisions (for example, cross-functional or mixed business process).

One of the most important criteria of CL is the difficulty of replacing CE. This is because each COS position has an estimate of the cost of replacing its incumbent, expressed as an estimate of the sum of costs from different types of sources:

- difficulty in finding a competent specialist;
- the recruitment duration for the position of CE;
- probability of mistakes in recruiting;
- duration of the period of adaptation of a new employee;
- the degree of performance degradation during the adaptation period;
- demotivation of employees during the period of personnel rotation;
- the decreased discipline of personnel in a situation of staff turnover;
- a corporate culture that does not promote synergistic effects from the work of the organization;
- the income level of an employee in the position of CE;
- securing the position with compensation and social packages;
- model of administrative and functional subordination.

An important factor in assessing CL of CE is the features of the management system implemented in COS. The controllability rate can be one of the important criteria for determining the criticality level of system elements [24, 25]. In this case, it is necessary to take into account not only administrative management but also functional. We will schematically consider the model of functional control. There are two types of management in COS:

- administrative, when the head of the unit is responsible for the overall organization of the activities of the unit's employees, for the quality performance of functional duties, for the volume of tasks assigned to subordinates and their results, as well as for the fulfillment by the unit's employees of all formal requirements for personnel;
- functional, when the manager organizes the activities of an employee who performs a function in the area of responsibility of this manager, and the resource of the employee's working time is managed by the administrative manager.

To formalize this fundamental aspect of the functioning of COS, we present a model of the functional management of COS. It should be noted that in most of the current COS the corporate structure does not coincide with the legal one due to a number of objective and subjective reasons. Therefore, in system organizations, a scheme is established for the distribution of power and interaction between administrative management and functional management [26, 27].

The scheme of power sharing and interaction between the administrative and functional managers is represented in Table 1.

Regarding CE, it should be noted that the functional manager must agree in advance with the administrative manager on the hiring, dismissal, and vacation of employees with key functions who are directly subordinate to the administrative manager.

6. Approaches to determining the criticality level and measurement scale

At least three approaches can be applied to the definition of CL for the elements of COS, which determine the numerical indicators of the influence of the elements on the quality of functioning and the FS indicators of COS as a whole:

- expert approach;
- analytical (criteria) approach;
- expert-analytical.

Table 1
The scheme of power sharing and interaction between the administrative and functional managers

Interaction parameters	Functional manager	Administrative manager	CEO
1. Participation of the manager in the employee's career			
1.1. Coordination of the introduction of new positions	Initiates	Agrees, signs the order	Approves the memo
1.2. Recruitment	Makes a decision	Signs the order	Agrees for N-1 level subordinates
1.3. Adaptation procedure	Joint participation		
1.4. Transfer to another position within the scope of official duties	Makes a decision	Agrees, signs the order	Agrees for N-1 level subordinates
1.5. Vacation	Agrees	Approves, signs the order	
1.6. Dismissal	Initiates	May initiate and approve the order	Agrees for N-1 level subordinates
2. The manager's influence on the salary level	Initiates	Agrees, signs the order	Approves a memo when the budget is exceeded
3. Bonuses for subordinates	May initiate and approve the initiative of the administrative manager	Initiates	Approves the memo
4. Degree of control and interaction	Regarding performance of functions in the area of responsibility	Regarding labor discipline and performance of basic functions	
5. Providing functional subordinates with resources (information, labor, material)	Provides support	According to the standards adopted for all COS employees	
6. Using budgets by subordinate employees	Monitoring the implementation of the approved budgets accordingly	Control over working hours	
7. Duties of the manager to control the professional activities of the employee	On professional issues in the context of COS activities	On general official issues of work in COS	
8. Business trip	Initiates, agrees	Signs the order after approval by the functional manager	
9. Bonus cancellation	Initiates, agrees	May initiate, signs the order after approval by the functional manager	

The analytical approach provides a parametrization of the CE concept and describes this indicator in an analytical form [28]. CL is based on the number of subordinates and the impact on financial and information flows. The advantage of this approach is the clarity and transparency of the CL calculation result. Among the shortcomings, it should be noted the possible incompleteness of the mathematical model of CE.

The expert approach is the opposite of the analytical one. You require the participation of qualified experts who understand the specifics of the device industry, and the specific COS. But this is compensated by the fact that experts can make a more comprehensive and detailed assessment. Due to the participation of a large number of experts, the human factor is almost completely eliminated, since it is unlikely that a large number of experts will make the same estimation error. Among the risks, it should be noted that when creating questions posed to experts, emphasis can also be deliberately or spontaneously placed on some tendentious aspects of COS.

In turn, the expert approach can be based on the application of:

- ordinal scales;
- cardinal scales of expert evaluation.

For ordinal scales, advantage ratios can be given in the form:

- ranking of alternatives (strict or non-strict);
- matrices of pairwise comparisons of alternatives in a qualitative form (strict or non-strict);
- multiple comparisons of alternatives (strict or non-strict);
- incomplete rankings of alternatives (strict or non-strict).

For cardinal scales, advantage ratios can be given in the form:

- metricized matrices of pairwise comparisons;
- scoring of alternatives;
- relative weights of alternatives.

In turn, the weighting coefficients can be:

- normalized;
- centralized;
- idealized;
- in interval form;
- in the form of membership functions to a fuzzy set.

The expert-analytical approach is a combination of expert and analytical approaches. The computational experiment described in this paper was conducted on its basis.

A feature of modeling the criticality of elements of a complex system is that the data used to analyze and compare criticality are measured or evaluated on different scales. Therefore, combined data into aspects for each system element could be aggregated in various forms:

- defining discrete criticality levels;
- evaluating the membership function of element criticality to a fuzzy set;
- determining the intervals of criticality values for each element;
- calculating the intervals of criticality values for each element in metricized scales.

7. Diagram of precedents in determining the criticality level

To illustrate the processes carried out in the organization when determining the CL, it is advisable to give a diagram of precedents that reflects the relationship between actors in the process of determining the CE and quantifying the LC. Such a diagram is presented in Figure 1.

Based on this diagram, the researcher could formally assess various aspects of the CE activity and quantify the CL.

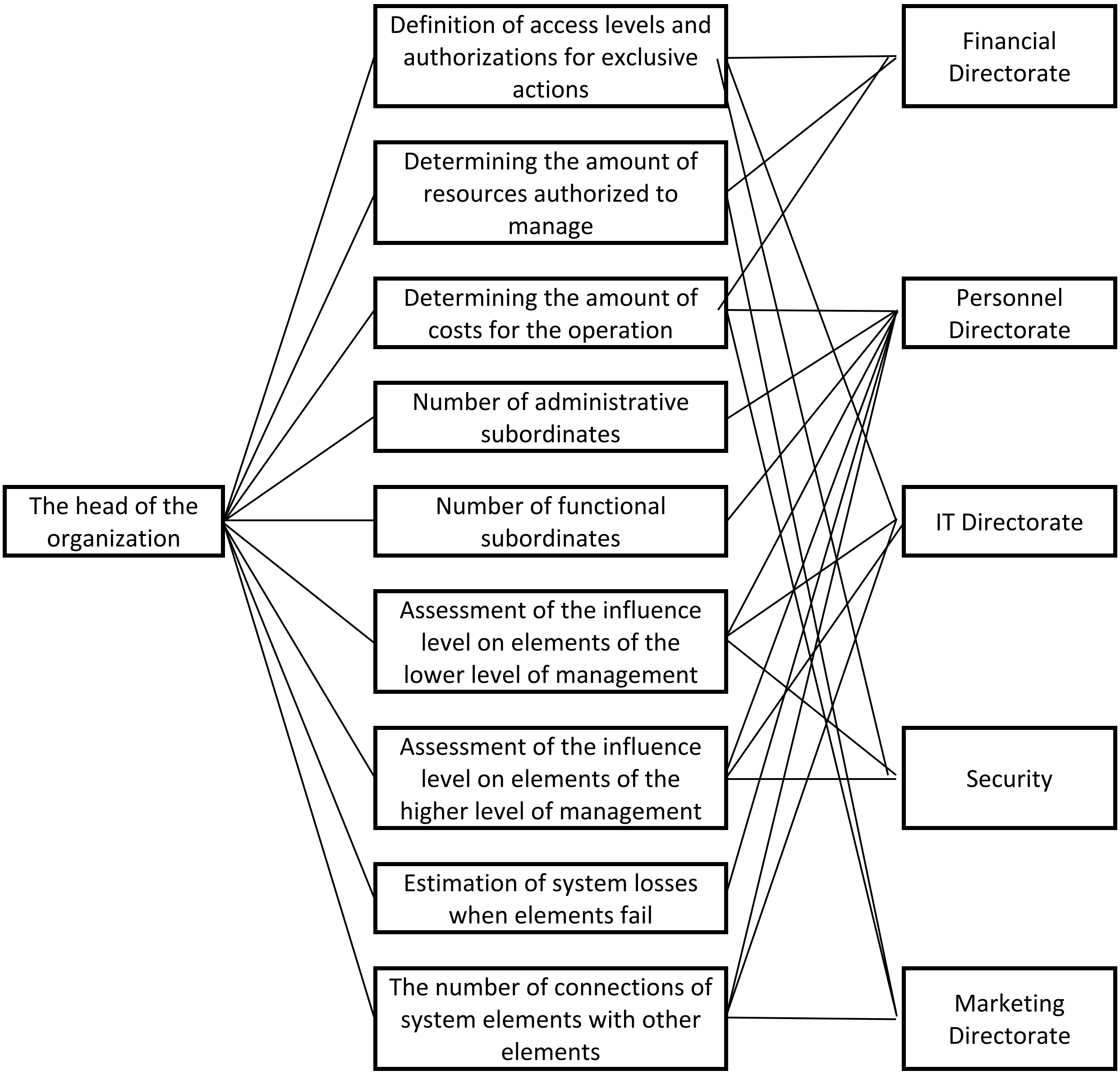

Figure 1: A use case diagram for identifying critical elements and evaluating CL

8. Additional information to clarify the criticality level

Additional information can be used to improve the accuracy of determining CL: the responsibility matrix and the authority matrix.

The RACI (Responsible, Accountable, Consulted, Informed) matrix can be a special aspect that characterizes the system elements represented by the graph nodes because this matrix provides a description and coordination of the structure of responsibility for the implementation of work packages in projects and business processes performed by the system elements. The RACI matrix is a form of describing the distribution of responsibility for the job implementation on a business process project, indicating the role of each element of the system in its implementation. The RACI matrix is a convenient tool for allocating responsibilities between the elements of the system: Responsible, Accountable, Consulted and/or Informed. Based on the analysis of these roles of elements in the operation of the system, a conclusion can be drawn regarding the criticality of each element.

An important tool for determining the CL is also the authority matrix (AM), which is developed and approved in each system COS. AM describes the authority levels of key managers in all major areas of COS activity. Therefore, the local CL indicators for this matrix can be easily folded and digitized.

9. Methods for metrization of rankings of alternatives specified in ordinal scales

The issue of determining the complete order of a set of objects is a frequent task of expert evaluation and has many practical applications [29-31]. But often the information about the advantages in the ordinal scale on the set of alternatives is incomplete and insufficient, and therefore cannot satisfy the researcher in all cases [32, 33]. In addition, it is not always possible to adequately apply the entire arsenal of mathematical methods using expert data on the ratio of advantages in this form of advantage aspect [34, 35].

To date, a significant number of complex procedures for the metrization of features specified in an ordinal scale have been developed [36, 37]. But the metrization procedures have a number of disadvantages:

- they are usually too time-consuming for an expert;
- sometimes the expert is forced to change the advantages in the process of refining his judgments, since the requirement to provide a numerical assessment of the still insufficiently formalized phenomenon under study may turn out to be too strict;
- during metrization, some information about the structure of the expert's advantages may be lost due to the approximation of a whole range of possible relationships by vectors of numerical values.

Let us describe a group of methods developed by the authors that allow us to carry out a consistent metrization of the advantages given by an expert on an ordinal scale, making these transformations automatically, without the participation of an expert. Quantitative data on benefits are presented, as a rule, in interval form. Fixed values of weight coefficients of objects are also calculated, which can be further used in methods that do not allow the use of interval estimates.

Among the common ways to represent the values of weight coefficients, real numbers are most often used, taking into account the normalization condition [38, 39]:

$$\sum_{i\in I}\rho_i = 1, \tag{1}$$

$$\rho_i > 0,\ i \in I = \{1,...,n\}, \tag{2}$$

where n – number of alternatives.

9.1. Finding the gravity center

Without diminishing the generality, we assume that the expert has established the advantage relation on the set of objects in the form of a strict ranking as follows: $a_1 \succ a_2 \succ ... \succ a_n$. Then the simplex corresponding to this relation is given as the intersection of such a system of half-spaces, taking into account condition (2):

$$\begin{aligned} &1 > \rho_1, \\ &\rho_1 > \rho_2, \\ &\cdots\cdots \\ &\rho_{n-1} > \rho_n, \end{aligned} \tag{3}$$

$$\sum_{i\in I}\rho_i \le 1. \tag{4}$$

If the equal sign occurs in system (3) times, then the number of inequalities of the form (3) decreases and the dimension of the simplex decreases accordingly. That is, the area of possible values of the weight coefficients of objects in this case $(n-s-1)-$ is a dimensional simplex.

For definiteness, we introduce a heuristic.

Heuristic E1. The gravity center of the simplex (3), (4), which is calculated by the formula

$$\rho_i = \left(\sum_{j\in I} x_j^i\right)/n,\ i\in I,$$

we will consider the point that approximates the area of change of the weight coefficients.

The coordinates of the vertices of this simplex, which are denoted by $x_j = \left(x_j^1,...,x_j^n\right),\ j = 1,...,n+1,$ calculated as follows:

$$x_j = \left(1/j,\ 1/j,...,0,...,0\right),\ j = 1,...,n+1.$$

The number of non-zero elements of the vector x_j is equal to $j < n,$ and the number of zero components $\left(n+1-j\right).$ At the same time, the $\left(n+1\right)$ vertex of the simplex is at the origin of coordinates: $x_{n+1} = \left(0,...,0\right).$ It is obvious that the point $\rho = \left(\rho_1,...,\rho_n\right)$ lies on the hyperplane described by equation (1) and, thus, satisfies the condition of normalization of weight coefficients.

9.2. Normalization of the midpoints of the intervals of changes in weighting coefficients

Let all inequalities of the system (3) be strict. Then, considering the components of the vector of weight coefficients of objects to be independent and taking into account inequalities of the form (3) and restrictions on the normalizability of weight coefficients (1), (2), it is easy to verify that the intervals of variation of the vector components ρ are as follows:

$$\rho_1 \in \left(1/n,\ 1\right),...,\rho_i \in \left(0,\ 1/i\right),\ i = 2,...,n.$$

If the first relations between the alternatives are equalities, that is,

$$1 > \rho_1 = ... = \rho_{S+1} > ... > \rho_n > 0,$$

Then the corresponding weight coefficients belong to the intervals $\rho_1 \in \left(1/n, 1/\left(s+1\right)\right),...,\rho_{S+1} \in \left(1/n, 1/\left(s+1\right)\right).$

Thus, the intervals of changes in the weight coefficients of objects, that is, the hyperparallelepiped of weight coefficients (HWC), in this case, are as follows

$$\rho_1 \in \left(1/n, 1\right),\ \text{if } a_1 > a_2,$$

$$\rho_i \in \left(1/n, 1/\left(s+1\right)\right),\ i = 1,...,s,\ \text{if } a_1 \sim a_2 \sim ... \sim a_S > a_{S+1},$$

$$\rho_i \in \left(0, 1/i\right),\ i = 2,...,n,\ \text{if } a_1 > a_2 > ... > a_n.$$

Heuristic E2. To approximate the obtained HWC by a normalized vector, its center is selected.

That is, the average value of the HWC, calculated by applying the proposed procedure

$$\rho_i^C = \left(\rho_i^H + \rho_i^B\right)/2,\ i \in I, \qquad (5)$$

where $\rho_i^H, \rho_i^B\ i \in I, -$ respectively, the lower and upper limits of the change in the relative importance of the $i-$th object.

At the last stage of the procedure, the average values of the HWC should be normalized

$$\rho_i = \rho_i^C / \sum_{j \in I} \rho_i^C,\ i \in I. \qquad (6)$$

9.3. Calculation of weight coefficients based on the average value of the largest coefficient

Let conditions (2)-(4) be satisfied. Let's introduce such a heuristic.

Heuristic E3. The values of the weight coefficient of the "best" object are selected from the interval $\left(1/n, 1\right).$

The value of the largest weight coefficient will be chosen as the midpoint of the interval introduced by the E3 heuristic:

$$\rho_1^C = \left(1/n + 1\right)/2 = \left(n+1\right)/2n.$$

The selected value determines the interval for selecting the next weighting factor, i.e., $\rho_2^C \in \left(0, \min\left(1/2, \rho_1^C\right)\right)$ and so on. If $\left(i-1\right)$ coefficients are chosen, then the next average value of the interval is calculated according to the formula (5), in which $\rho_i^H = 0,\ \rho_i^B \in \left(1/i, \rho_{i-1}^C\right),$ due to the system of restrictions (3), we have the inequality $\rho_i > \rho_{i-1}$.

If some restrictions of the system (3) are equations $\rho_i = \rho_{i-1}$, $1 < i < n-1,$ then the boundaries of the intervals are calculated by the formulae $\rho_i^H = 0,\ \rho_i^B \in \left(1/\left(i+s+1\right), \rho_{i-1}^C\right),\ \ j = i,...,i+s+1,$ where $s-$ is the number of equations. Thus, the parallelepiped of possible values of the weight coefficients of objects is as follows:

$$\rho_1^H = 1/n,\ \ \rho_1^B = 1,$$
$$\rho_i^H = 0,\ \ \rho_i^B \in \left(1/i, \rho_{i-1}^C\right),\ \text{if}\ a_1 > a_2 > ... > a_n,$$
$$\rho_i^H = 0,\ \ \rho_i^B \in \left(1/\left(i+s+1\right), \rho_{i-1}^C\right),\ \ j = i,...,i+s+1,$$
$$\text{if}\ a_j \sim a_{j+1} \sim ... \sim a_{j+S},\ 1 \le i \le n-s,$$

where the values $\rho_i^C, i \in I,$ are calculated by the formula (5).

9.4. Calculation of weight coefficients based on the average value of the smallest coefficient

This method differs from the previous one in that it is based on the introduction of a different heuristic.

Heuristic E4. The value of the weight coefficient of the "worst" object is selected from the interval $\rho_n \in \left(0, 1/n\right)$.

The value of the smallest weight coefficient is set equal to the value $\rho_n^C = 1/2n.$ The values of the lower bounds of the i-th interval are determined by formulae $\rho_i^H = \min\left(1/n, \rho_{i+1}^C\right)$ due to the inequality $\rho_i > \rho_{i-1}$ of system (3), and the values of the upper bounds are assumed to be equal $\rho_i^B = 1/i,\ i = 2,...,n.$ Interval midpoints $\rho_i^C, i \in I,$ are calculated by formula (5). After that, the values $\rho_i^C, i \in I,$ are normalized by formula (6).

9.5. Method of equal intervals

To calculate the boundaries of the intervals of changes of weight coefficients, we first use their point estimates. Let $\alpha_n^H = \alpha,$ where $\alpha > 0-$ any positive number. We introduce the following heuristic.

Heuristic E5. The following assumptions are correct:

- if the objects are equal $a_i \sim a_{i+1}$, then $\alpha_i^H = \alpha_{i+1}^H,\ \alpha_i^B = \alpha_{i+1}^B;$
- if $a_i \ge a_{i+1}$, then $\alpha_i^H = \alpha_{i+1}^H,\ \alpha_{i+1}^B = \alpha_i^B + \alpha/2;\ \alpha_i^B = \alpha_i^H + \alpha;$
- if $a_i > a_{i+1}$, then $\alpha_i^B = \alpha_i^H + \alpha,\ \alpha_i^H = \alpha_{i+1}^H.$

To calculate the boundaries of changes in the weight coefficients of objects, we normalize the estimates obtained using the E5 heuristic according to the formulae

$$\rho_i^H = \alpha_i^H / \left(\sum_{j \in I} \alpha_j^H - \alpha\right),\ i \in I,$$

$$\rho_i^B = \alpha_i^B / \left(\sum_{j \in I} \alpha_j^B - \alpha\right),\ i \in I.$$

The given methods of metrization of the advantages specified in the ordinal scale have a number of positive properties:

- the expert is required to specify only the facts of the advantage between the objects because the metrization of the advantages is performed automatically and does not require the use of complex procedures for determining the intensity of the advantages;
- the obtained numerical values adequately reflect the expert's advantages, and do not change the structure of the advantages on the set of objects;
- calculated as a result of the application of HWC methods, better reflect the psychological characteristics of a person who is characterized by vague, inaccurate expert assessments.

These methods can also be used as a first approximation to apply more complex benefit metric procedures. At the same time, in the case of calculating the HWC, information about the advantages of an expert, expressed on an ordinal scale, is not lost.

10.Determining the aggregate value of the criticality level

The accumulated experience of expert assessment in various fields of human activity convincingly indicates that any statistical calculations become more useful and justified while decreasing the number of features to be analyzed [40, 41]. Therefore, there is an opportunity for expert assessment to aggregate features of objects into a smaller number of constructed factors, aspects, etc. [42, 43].

10.1. Metrics used in expert evaluation issues

The following metrics could be used to determine distance between rankings of alternatives:

- Cook's metrics of mismatch of ranks (places, positions) of alternatives

$$d\left(R^j, R^l\right) = \sum_{i\in I}\left|r_i^j - r_i^l\right|,$$

where $r_i^l -$ the rank of $i-$th alternative by $l-$th expert, $R^l,\ l \in L,\ 1 \le r_i^l \le n,$

- Heming's metrics;
- Euclid's metrics;
- elements of a vector of advantages, are the number of alternatives preceding each alternative in the ranking.

10.2. Generalized quality criteria

Constructing a convolution (a generalized, aggregating, integral criterion for the quality of an object) means supplementing a partial order on a set of objects to a complete one [29, 30]. This can be done in many ways, and necessarily involves an element of subjectivity [41]. Therefore, the convolution method must be justified only to the following extent: the total order generated by the convolution must be consistent with the natural partial order. Some of the most common convolution families are:

- linear convolution

$$Q_i^{(1)} = \sum_{j\in J}\rho_j \omega_i^j,\ i \in I,$$

- multiplicative convolution

$$Q_i^{(2)} = \prod_{j\in J}\rho_j \omega_i^j,\ i \in I,$$

- a generalized convolution of indicators, which is sometimes also called the "bottleneck" principle

$$Q_i^{(3)} = \max_{j\in J}\rho_j \omega_i^j,\ i \in I,$$

where $\omega_i^j, i \in I, j \in J, -$ the normalized values of the parameters of objects $a_i^j, i \in I, j \in J,$ are determined by transformations (1.6) - (1.13). Sometimes a convolution of the following form is also used

$$Q_i^{(4)} = \prod_{j\in J} \rho_j \left(\left(\omega_i^j - \min_{j\in J} \omega_i^j \right) / \min_{j\in J} \omega_i^j \right),\ i \in I.$$

In some papers, such an approach is proposed to determine the complete order on a set of objects. The set of parameter sets corresponds to a certain "cloud" of points in a multidimensional space. If it is assumed that each object has a unit mass, then the Karhunen-Loev transformation makes it possible to find some axis passing through the midpoint (the gravity center of objects), around which the moment of inertia of the system of points is the smallest. After centering the object parameter values

$$\omega_i^{j(Ц)} = \frac{1}{n} \sum_{i\in I} \omega_i^j,\ i \in I, j \in J,$$

the gravity center of objects is at the origin of coordinates and the straight line V passes through it. Then the issue is reduced to finding such a straight line V for which the following functional reaches a minimum

$$Q^{(5)} = \sum_{i\in I} \left\| \omega_i^{j(Ц)} - pr_V \omega_i^{j(Ц)} \right\|^2,$$

where $\omega_i^{(Ц)}$ – row vector of the normalized matrix of parameter values, $pr_V \omega_i^{(Ц)}$ – row vector of the object projection $\omega_i^{(Ц)}$ on the axis V, $\| \cdot \|$ – distance between points $\omega_i^{(Ц)}$ and $pr_V \omega_i^{(Ц)}$. To determine the quality of a set of parameters, the distances from the projections of objects $pr_V \omega_i^{(Ц)}$ to the projection of some ideal (utopian) object onto the axis V are considered. This method can be generalized to the case of weighted parameter values, and also if some a priori "qualities" of objects are known.

Sometimes a generalized criterion for the quality of objects is introduced as

$$Q_i^{j(6)} = \sum_{l=1}^{j} \omega_i^l,\ i \in I,$$

where ω_i^l – normalized values of object parameters. The best object is considered to have the value of indicators $Q_i^{j(6)}$ for $\forall j \in J, i \in I$, better than the corresponding values of other objects and best coincides in direction with the hypothetical ideal vector $Q_i^{j(6)}, j \in J$, the value of all elements of which are equal to one. Sometimes convolution is used to aggregate information across objects.

$$Q^{(7)} = \frac{1}{m} \sum_{j\in J} \left(\omega_i^{j(Ц)} \right)^2,$$

where $\omega_i^{j(Ц)} = \left(\omega_i^j - \omega_j^C \right) / \left(\frac{1}{n} \sum_{i\in I} \left(\omega_i^j - \omega_j^C \right) \right)^{1/2}, i \in I, j \in J,\ \omega_j^C = \frac{1}{n} \sum_{i\in I} \omega_i^j.$

It should be noted that with non-linear functions of indicators, it is difficult for an expert to interpret his wishes in terms of the weight of the indicators, which significantly reduces the value of this approach.

11. Computational experiment

To determine the feasibility of using the approaches described in this paper, a computational experiment was conducted. The experiment was carried out based on one of the largest domestic system companies. The object of the study was the management company of the holding, which employs more than a hundred employees. The holding staff is several thousand people. Volumes of financial, material, service flows, etc. constitute a trade secret and are not subject to disclosure. The name of the company, positions of experts, and positions of CE also do not need to be disclosed.

To determine the compromise solutions to the issue of multi-attribute choice that arises in the analysis of expert information on the ranking of CE, two criteria were applied: minimax and additive. Moreover, if the values of the aggregated variant by these criteria turned out to be non-dominated, all of them were included in the set of effective solutions for further analysis and metrics.

11.1. Conditions of the experiment

To conduct a computational experiment, it was decided to use a combined approach to determining the CL.

At the first stage of the computational experiment, 6 experts were selected who are best oriented in the situation regarding the activities of the organization under study and have the most inclusive information about the managers of this organization, about the management of resources and flows of the organization, etc.

In the second stage, the normalized coefficients of relative competence of experts were determined using the methods of self-assessment and mutual assessment.

In the third stage, five employees were identified by the expert method among all the employees of the company. According to the experts, these employees are the CE of the organization. Through the introduction of expert technologies, it is necessary to find the quantitative characteristics of the CL of these CE.

Since it is a difficult task for a person to assign cardinal relationships between alternatives, it was decided to receive information from experts in ordinal scales - in the form of rankings on a set of CE selected by experts.

The main features of the definition of CE of COS are the definitions of CL:

- by functionality;
- by authority level;
- by the impact on the operation of the system as a whole;
- by influence on the external manifestations of the system;
- by influence on the main flows in the system;
- by the impact on system resources.

11.2. Determining the compromise rankings on the set of CE

When determining the order of importance of CE by functionality, expert rankings of CE by this indicator are summarized in Table 2.

Table 2

Determining the ranking of CL of CE by their functionality

Expert	Expert competence coefficient	The rank of CE given by the expert	The value of the minimax criterion	The value of the additive criterion
Expert 1	0,3	$a_5 \succ a_1 \succ a_4 \succ a_3 \succ a_2$		
Expert 2	0,2	$a_4 \succ a_2 \succ a_3 \succ a_1 \succ a_5$		
Expert 3	0,2	$a_5 \succ a_3 \succ a_4 \succ a_2 \succ a_1$		
Expert 4	0,1	$a_4 \succ a_3 \succ a_5 \succ a_1 \succ a_2$		
Expert 5	0,1	$a_5 \succ a_2 \succ a_4 \succ a_1 \succ a_3$		
Expert 6	0,1	$a_5 \succ a_1 \succ a_3 \succ a_4 \succ a_2$		
Compromise ranking		$a_5 \succ a_4 \succ a_3 \succ a_1 \succ a_2$	8	30

Expert rankings of CE by the level of their powers are given in Table 3.

Table 3
Determining the ranking of CL of CE by the level of their authority

Expert	Expert competence coefficient	The rank of CE given by the expert	The value of the minimax criterion	The value of the additive criterion
Expert 1	0,3	$a_4 \succ a_2 \succ a_5 \succ a_3 \succ a_1$		
Expert 2	0,2	$a_4 \succ a_1 \succ a_2 \succ a_3 \succ a_5$		
Expert 3	0,2	$a_5 \succ a_4 \succ a_3 \succ a_1 \succ a_2$		
Expert 4	0,1	$a_5 \succ a_2 \succ a_4 \succ a_3 \succ a_1$		
Expert 5	0,1	$a_5 \succ a_3 \succ a_4 \succ a_2 \succ a_1$		
Expert 6	0,1	$a_5 \succ a_2 \succ a_1 \succ a_4 \succ a_3$		
Compromise ranking		$a_5 \succ a_4 \succ a_2 \succ a_3 \succ a_1$	8	28

Expert rankings of CE in terms of their impact on the operation of the system as a whole are presented in Table 4.

Table 4
Determining the ranking of CL of CE according to the impact on the operation of the

Expert	Expert competence coefficient	The rank of CE given by the expert	The value of the minimax criterion	The value of the additive criterion
Expert 1	0,3	$a_5 \succ a_3 \succ a_4 \succ a_2 \succ a_1$		
Expert 2	0,2	$a_4 \succ a_1 \succ a_3 \succ a_2 \succ a_5$		
Expert 3	0,2	$a_5 \succ a_4 \succ a_2 \succ a_1 \succ a_3$		
Expert 4	0,1	$a_4 \succ a_2 \succ a_5 \succ a_3 \succ a_1$		
Expert 5	0,1	$a_5 \succ a_4 \succ a_3 \succ a_2 \succ a_1$		
Expert 6	0,1	$a_4 \succ a_3 \succ a_1 \succ a_5 \succ a_2$		
Compromise ranking		$a_4 \succ a_5 \succ a_3 \succ a_2 \succ a_1$	6	28

Expert rankings of CE by influence on the external manifestations of the system are presented in Table 5.

Table 5
Determining the ranking of CL of CE according to the influence on the external manifestations of the system

Expert	Expert competence coefficient	The rank of CE given by the expert	The value of the minimax criterion	The value of the additive criterion
Expert 1	0,3	$a_5 \succ a_1 \succ a_4 \succ a_2 \succ a_3$		
Expert 2	0,2	$a_4 \succ a_3 \succ a_2 \succ a_1 \succ a_5$		
Expert 3	0,2	$a_5 \succ a_3 \succ a_2 \succ a_4 \succ a_1$		
Expert 4	0,1	$a_5 \succ a_3 \succ a_4 \succ a_1 \succ a_2$		
Expert 5	0,1	$a_3 \succ a_2 \succ a_4 \succ a_1 \succ a_5$		
Expert 6	0,1	$a_5 \succ a_2 \succ a_4 \succ a_3 \succ a_1$		
Compromise ranking		$a_5 \succ a_3 \succ a_4 \succ a_2 \succ a_1$	6	28

Expert rankings of CE by the impact on the main flows in the system are given in Table 6.

Table 6

Determining the ranking of CL of CE by the impact on the main flows in the system

Expert	Expert competence coefficient	The rank of CE given by the expert	The value of the minimax criterion	The value of the additive criterion
Expert 1	0,3	$a_5 \succ a_1 \succ a_2 \succ a_3 \succ a_4$		
Expert 2	0,2	$a_5 \succ a_2 \succ a_3 \succ a_1 \succ a_4$		
Expert 3	0,2	$a_3 \succ a_5 \succ a_4 \succ a_2 \succ a_1$		
Expert 4	0,1	$a_3 \succ a_4 \succ a_5 \succ a_1 \succ a_2$		
Expert 5	0,1	$a_4 \succ a_2 \succ a_5 \succ a_1 \succ a_3$		
Expert 6	0,1	$a_5 \succ a_1 \succ a_4 \succ a_3 \succ a_2$		
Compromise ranking		$a_5 \succ a_4 \succ a_3 \succ a_1 \succ a_2$	8	36

Expert rankings of CE by the impact on system resources are presented in Table 7.

Table 7

Determining the ranking of CL of CE by the impact on system resources

Expert	Expert competence coefficient	The rank of CE given by the expert	The value of the minimax criterion	The value of the additive criterion
Expert 1	0,3	$a_4 \succ a_1 \succ a_5 \succ a_2 \succ a_3$		
Expert 2	0,2	$a_3 \succ a_2 \succ a_4 \succ a_1 \succ a_5$		
Expert 3	0,2	$a_5 \succ a_2 \succ a_4 \succ a_3 \succ a_1$		
Expert 4	0,1	$a_5 \succ a_3 \succ a_4 \succ a_1 \succ a_2$		
Expert 5	0,1	$a_5 \succ a_2 \succ a_3 \succ a_1 \succ a_4$		
Expert 6	0,1	$a_5 \succ a_1 \succ a_2 \succ a_4 \succ a_3$		
Compromise ranking 1		$a_5 \succ a_3 \succ a_4 \succ a_1 \succ a_2$	8	36
Compromise ranking 2		$a_5 \succ a_2 \succ a_4 \succ a_1 \succ a_3$	10	34
Compromise ranking 3		$a_5 \succ a_2 \succ a_4 \succ a_3 \succ a_1$	10	34

Compromise rankings of CL of CE according to various aspects of the impacts on COS are summarized in Table 8.

Table 8
Compromise rankings of CL of CE according to various aspects of impacts on COS

Compromise ranking of CL of CE	The rank of CE given by the expert	The value of the minimax criterion	The value of the additive criterion
By the functionality	$a_5 \succ a_4 \succ a_3 \succ a_1 \succ a_2$	8	30
By authority level	$a_5 \succ a_4 \succ a_2 \succ a_3 \succ a_1$	8	28
By the impact on the operation of the system as a whole	$a_4 \succ a_5 \succ a_3 \succ a_2 \succ a_1$	6	28
By influence on the external manifestations of the system	$a_5 \succ a_3 \succ a_4 \succ a_2 \succ a_1$	6	28
By influencing the main flows in the system	$a_5 \succ a_4 \succ a_3 \succ a_1 \succ a_2$	8	36
By impact on system resources 1	$a_5 \succ a_3 \succ a_4 \succ a_1 \succ a_2$	8	36
By impact on system resources 2	$a_5 \succ a_2 \succ a_4 \succ a_1 \succ a_3$	10	34
By impact on system resources 3	$a_5 \succ a_2 \succ a_4 \succ a_3 \succ a_1$	10	34

11.3. Calculation of aggregated quantitative CL for selected CE

The method of calculating weighting coefficients based on the average value of the smallest coefficient, described in paragraph 9.4, was applied to the compromise rankings of CL of CE presented in Table 8. The calculation results and averaged normalized CL values are presented in Table 9.

Table 9
Compromise rankings of CL of CE according to various aspects of the impacts on COS

Compromise ranking of CL of CE	The rank of CE given by the expert	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5
By the functionality	$a_5 \succ a_4 \succ a_3 \succ a_1 \succ a_2$	0,186	0,124	0,217	0,233	0,24
By authority level	$a_5 \succ a_4 \succ a_2 \succ a_3 \succ a_1$	0,124	0,217	0,186	0,233	0,24
By the impact on the operation of the system as a whole	$a_4 \succ a_5 \succ a_3 \succ a_2 \succ a_1$	0,124	0,186	0,217	0,24	0,233
By influence on the external manifestations of the system	$a_5 \succ a_3 \succ a_4 \succ a_2 \succ a_1$	0,124	0,186	0,233	0,217	0,24
By influencing the main flows in the system	$a_5 \succ a_4 \succ a_3 \succ a_1 \succ a_2$	0,186	0,124	0,217	0,233	0,24
By impact on system resources 1	$a_5 \succ a_3 \succ a_4 \succ a_1 \succ a_2$	0,186	0,124	0,233	0,217	0,24
By impact on system resources 2	$a_5 \succ a_2 \succ a_4 \succ a_1 \succ a_3$	0,186	0,233	0,124	0,217	0,24
By impact on system resources 3	$a_5 \succ a_2 \succ a_4 \succ a_3 \succ a_1$	0,124	0,233	0,186	0,217	0,24
The total value of the coefficients		1,24	1,43	1,61	1,81	1,91
Normalized average value		65%	75%	84%	94%	100%

Thus, the highest CL in quantitative terms has CE #5 – 100%, and the lowest CL has CE #1 – 65%.

12. Results

Thus, the CL of the system elements are being digitized and we can use the obtained values for additional motivation of critical elements, providing them with special funding, implementing security procedures, etc.

Considering the model of the form (1) we can settle that the influence of CE on FS of COS must be at least one or more orders greater than the effect of linear (non-critical) elements. This fact is confirmed by corresponding computational experiments.

The study proposes a model for determining CE of COS. It is also justified:

- model is eligible for defining critical parts;
- expert assessment is acceptable to evaluate CL of certain aspects of system elements;
- the proposed approach tested positive to determine the integral CL of elements of COS.

The conducted research suggests that in order to ensure the functional stability of a complex organizational system, it is important and necessary to identify and maintain the critical elements of such a system.

This given model can be applied to the various needs of any organization, as well as adjusted to other subject areas with hierarchies and interactions. The model assumes further improvement and can be focused on handling with fuzzy data.

This work proposed a mathematical model for the issue of determining critical nodes in complex organizational systems. It is also substantiated using graphs for modeling the relationships between the elements of the system. We considered the features of the phenomenon of criticality concerning elements, relations of elements and subsystems within a complex system. We outlined the main aspects of characteristics of organizational systems, which are essential to maintain coexistence of criticality and functional stability. It is considered the possibility of expert assessment in determining the criticality level of system elements in some aspects. The application of well-known approaches is justified for the allocation of critical elements of the system, in particular, the responsibility matrix.

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